Thermal control using liquid-metal bridge switches

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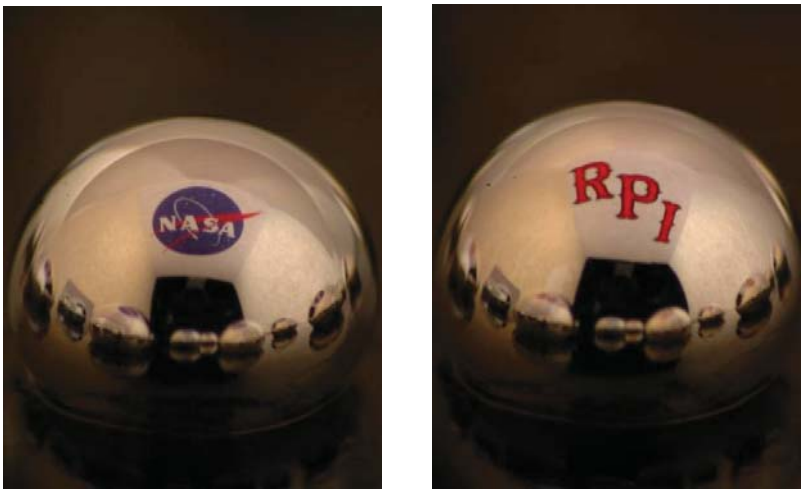

Fig. 1 The reflective surfaces of two unoxidized gallium satellite droplets act as convex mirrors.

1. Executive Summary

A short term effort (3-months) was undertaken to demonstrate the feasibility of a novel method to locally control the heat transfer rate and demonstrate the potential to achieve a turndown ratio of approximately 10:1. The technology had to be demonstrated to be at a TRL of 2-3, with a plan to advance it to a TRL 5-6. Here, we show that the concept recently developed in our laboratory, namely the pinned-contact, double droplet switch made by overfilling a hole drilled in a suitable substrate can be implemented with a low-melting temperature metal. When toggled near a second substrate, a liquid bridge can be reversibly connected or disconnected, on demand. We have shown experimentally that liquid-metal bridge switches can be made from gallium with a suitable choice of substrate materials, activation strategies, and control techniques. Individual as well as arrays of gallium bridge switches were shown to be feasible and can be robustly controlled. The very short response time of the bridge connection and disconnection (on the order of 1 millisecond) provides for utility in a wide range of applications. The liquid bridge switches may be controlled actively or passively. We have shown through computations and analysis that liquid bridge switches provide locally large turndown ratios (on the order of 10^3:1), so a relatively sparse packing of them would be needed to obtain the desired turndown ratio of 10:1. For the laboratory demonstrations, pressure activation was utilized. Simple designs for a passive control strategy are presented which are highly attractive for several reasons, including i) large turndown ratio, ii) no solid-moving parts, and iii) stable operation. Finally, we note that passive systems do not require any electronics for their control. This along with the relatively small molecular weight of candidate materials for the system, makes for a robust design outside of Earth's magnetic field, where spacecraft are subject to significant radiation bombardment.

2. Accomplishments

All of the tasks listed in the schedule proposed on April 8, 2013 (Figure 2) have been achieved. In addition, an analytical model of the array was developed and the results are now being compared to the numerical model (COMSOL).

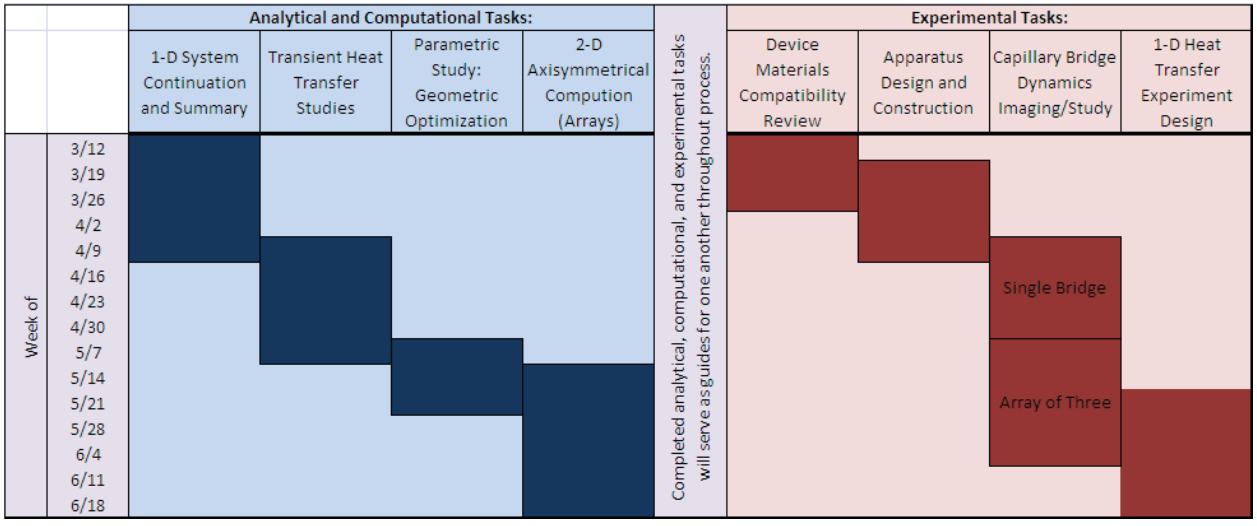

Fig. 2 Phase I detailed schedule proposed in the beginning of the project.

3. Scientific background

Liquid switches and bridges are possible by utilizing the surface tension and wetting characteristics of a liquid in a double droplet configuration. The double droplet system (DDS) is constructed by boring a hole into a plate and placing two droplets coupled through that cylindrical hole. Reversible DDS systems are only possible if the liquid is pinned to the sharp corner of the hole in the substrate which requires considerations for all system materials. A bi-stable switch with two equilibrium positions is possible when the volume of the two protruding droplets is greater than that of a sphere with a radius equal to that of the hole. This idea, previously demonstrated with water on a hydrophobic substrate (Teflon™), can also utilize a liquid metal such as gallium in order to create a system with significant heat transfer capabilities. The DDS switches comprised of various liquids can be actuated with a variety of mechanisms including pressure and electromagnetic forces. In order to form a liquid bridge, a satellite droplet or surface must be contacted by the DDS when it reaches its up state. Since surface tension creates a relatively large force at small scales compared to gravity or inertia, these DDSs are very stable against acceleration.

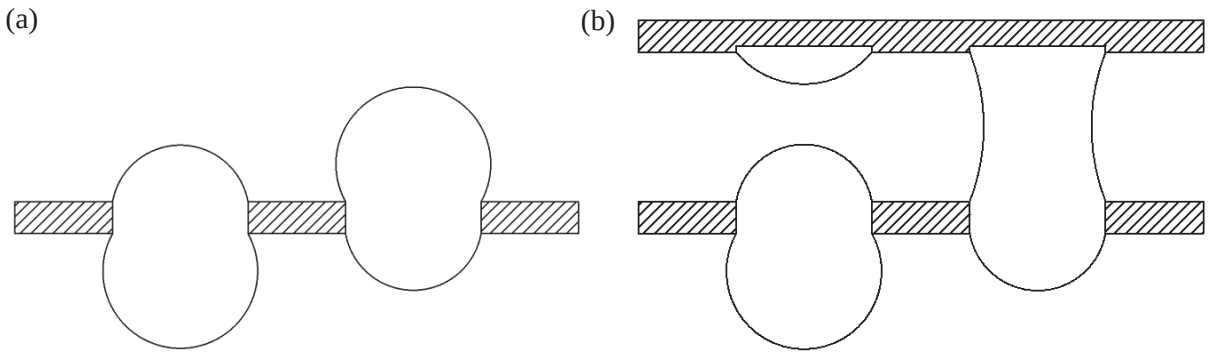

Fig. 3 (a) Schematic of a DDS switch showing the two possible equilibrium positions. (b) When a second substrate is nearby, a liquid bridge can be formed when the upwardly switched DDS and satellite droplet coalesce.

4. Experimental apparatus and procedures

4.1. Design of the physical system

Realizing a liquid-metal bridge switch system in practice requires insight in system geometry and physical chemistry of the liquid and the solid substrates. Since any physical system will currently be constrained to the Earth's surface, the capillary length scale (described by the Bond number, *Bo*) of whatever liquid-metal is to be utilized must be kept small (compared to unity) in the design of a device in order to be operational.

$$Bo = \frac{\rho g L^2}{\gamma}$$

Density is represented by ρ, gravity by *g*, the length scale by L, and surface tension by γ.

The substrate in a DDS system intended for use as a thermal control device needs a higher thermal conductivity than the polymers (Teflon™, Delrin™, and acrylic) that are typically used in these devices leaving metals as the candidate of choice. Since liquid-metals have a tendency to wet other metals, a polymeric coating is also a necessity for the metallic substrate. Fulfilling these two considerations, it is possible to pin a coupled droplet and satellite droplet on two coated metallic substrates. In the Off state, a relatively small amount of heat transfer through radiation and conduction through the shielding gas are present. When a pressure pulse switches the DDS upwards, it quickly coalesces with the satellite droplet forming a liquid bridge and a high thermal conductivity connection between the two plates. Pressure pulses provide the simplest system activation, however both active and passive activation using a variety of strategies are also possible.

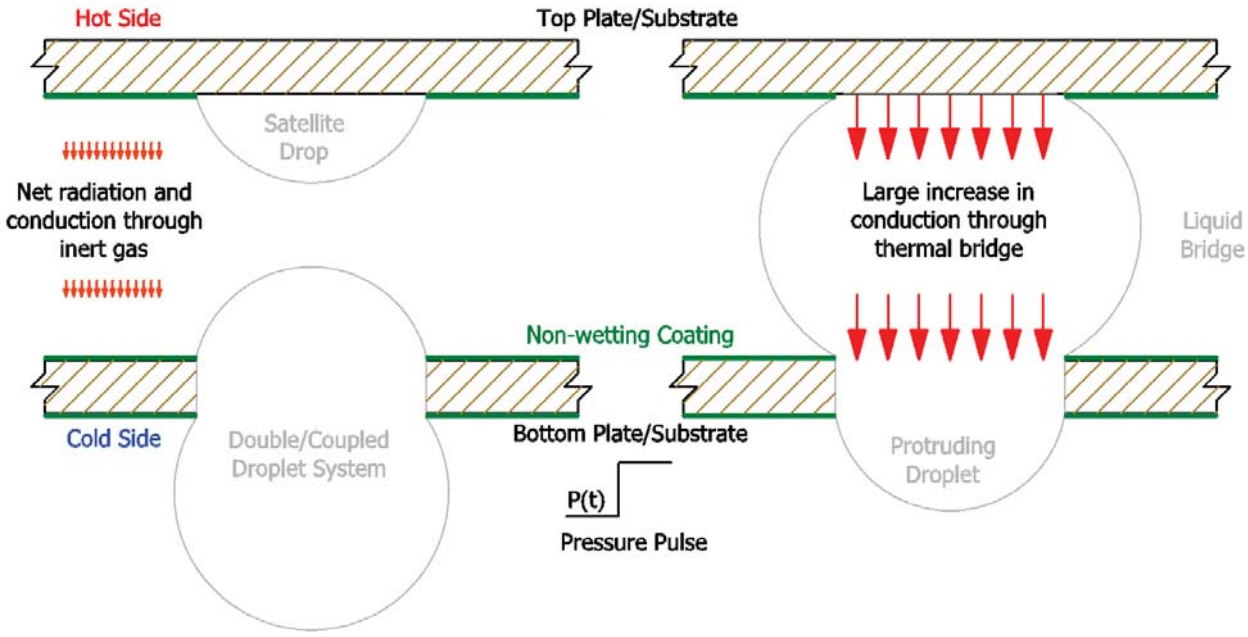

Fig. 4 Illustration of the mechanical, thermal, and material properties of a liquid bridge system for use in thermal control.

4.2. Materials-based design

4.2.1. Liquid-metal selection

In order to achieve conduction modulation through the proposed system, a material that is liquid at reasonably low temperatures, with a high thermal conductivity and a density to surface tension ratio which allows a reasonably sized DDS system is necessary. These very specific material constraints leave a narrow range of metals to choose from, which are summarized in Table 1.

Material	Surface Tension (dynes/ cm)		Density (g/cm^3)	Surface Tension/ Density	Melting Point (°C)	Thermal Conductivity (W/mK)	Notes
Elemental							
Gallium-Ga	725	at 25C	6.095	119	29.8	40.6	Oxidation
Mercury-Hg	461	at 22C	13.54	34	-38	8.3	Toxic, Low Vapor Pressure
Cesium-Cs	67.5	at 62C	1.843	37	28	35.9	Explodes on contact with H2O
Rubidium-Rb	84.7	at 39C	1.46	58	39	33.3	Explodes on contact with H2O
Alloys							
Gallistan™ Ga-In-Sn (62.5/21.5/16)	716	at 20C	6.44		-19	16.5	Oxidation
Cs-Rb (87/13)					-40		Oxidation/ Reaction with H2O
Cs-K (77/23)					-48		Oxidation/ Reaction with H2O

Table 1: Material properties of metals in the liquid phase near room temperature.

Perhaps, the first liquid-metal that comes to mind for this system would be mercury, the only elemental metal that is liquid at room temperature (20°C) and has reasonably large surface tension. However, large density, weak thermal properties, and toxicity, however, remove mercury from consideration for a liquid-bridge system. Alkali metals, such as cesium and rubidium, have reasonable physical properties and melting points similar to gallium, but are extremely sensitive to oxidation and volatile on contact with water. Alloying these metals amongst the alkali metals can give extremely low melting points, but would likely negatively affect their thermal properties and does not address their reactive nature.

Gallium, the elemental metal initially proposed for the thermal bridge, remains an extremely attractive option in comparison to the others considered due to a combination of moderate density, high thermal conductivity, and benignity to humans. To avoid surface oxidation, gallium must be handled under an inert gas such as argon, but is nowhere near as reactive as an alkali metal. Furthermore, temperature lower than the freezing point of gallium is required, the eutectic alloy of gallium, indium, and tin (with additional undisclosed additions such as silver) Gallistan™ , could be used but with a fairly significant penalty to thermal conductivity. Finally, note that gallium has a remarkably low viscosity (kinematic viscosity about 1/3 that of water), making it possible to design systems that waste very little energy and yet provide extremely fast response times. The experiments and entirety of analysis undertaken in Phase I of the project used gallium as the thermal bridge material.

4.2.2. Substrate selection

The unique properties of gallium require a survey of solid phase materials to construct the plate and substrate of the DDS switch system. Gallium readily alloys with many other metals causing a degradation of their structural properties. A material resistant to wetting by gallium or one that can be coated in wetting resistant material is also crucial, for pinning purposes. Large thermal conductivity and minimal density to reduce system weight should be accounted for during substrate selection. Table 2 shows a selection of materials reviewed in the search for a material with optimal combination of high conductivity, chemical stability, and low density.

Material	Thermal Conductivity (W/mK)	Density (g/cm^3)	Chemical compatibility with gallium	Notes
Copper	401	8.96	Moderately Resistant	Surface oxidation
Aluminum	237	2.7	Not Resistant, readily forms alloy	Surface oxidation
Tungsten	173	19.25	Extremely Resistant, will not form alloy	Machining difficulties
Magnesium	156	1.738	Moderately Resistant	Surface oxidation, pyrophoric tailings
Nickel	90.9	8.91	Moderately Resistant	
Tantulum	57.5	16.69	Extremely Resistant, will not form alloy	Machining difficulties, pyrophoric dust
Titanium	21.9	4.51	Moderately Resistant	

Table 2: Material properties and gallium compatibility of possible substrate metals.

Aluminum, a material that appears attractive at first glance, is entirely incompatible for the substrate and plate, as gallium quickly penetrates the grain boundaries of aluminum and causes degradation and structural failure. Other materials, such as tungsten and tantalum, resist alloying with gallium altogether; however their large densities are cause for concern when minimizing system weight.

Magnesium and copper resist degradation by gallium, with no noticeable damage to copper on multiyear timescales, and have desirable physical and thermal characteristics. Magnesium would benefit a system minimizing weight while copper has thermal properties that are the best among the materials reviewed. The surfaces of these two metals will oxidize at normal conditions in air with the oxidation process accelerating at higher temperatures. Since many of the polymeric coating processes for these materials occur at elevated temperatures, the process must be undertaken in an inert gas environment for optimal adhesion. Copper was selected as the substrate of choice for the experimental and computational models for Phase I because of its availability and machinability, but magnesium could be used in future systems.

4.3. Description of the experimental apparatus

A device was constructed in order to demonstrate liquid-metal bridges experimentally and to gain insight on future systems that measure heat transfer. A series of laser-cut acrylic plates were bonded together in order to hold two 38.1 x 38.1 x 1.59 mm (1.5” x 1.5” x 1/16”) copper plates in place; see Figure 5. The DDS is formed by drilling a 1.6 mm (0.063") diameter hole through one copper plate and the satellite drop substrate by drilling the same size hole partially into the other copper plate. These plates were then coated in epoxy spray paint to provide a non-wetting coating and drilled again to remove any excess coating. The acrylic cavity below the DDS is pressure sealed allowing a syringe or pump to provide an activation pulse through a PVC hose to the system. Silicone rubber gaskets provide seals and acrylic blocks act as spacers in the system. Although not used in the proof-of-concept experiments presented in this report, custom built nickel-chromium wire electrical resistance heaters were constructed and tested on the copper substrates. In order to prevent gallium oxidation during assembly and imaging, argon immersion tanks were utilized to provide an inert environment for the liquid-gallium bridge system.

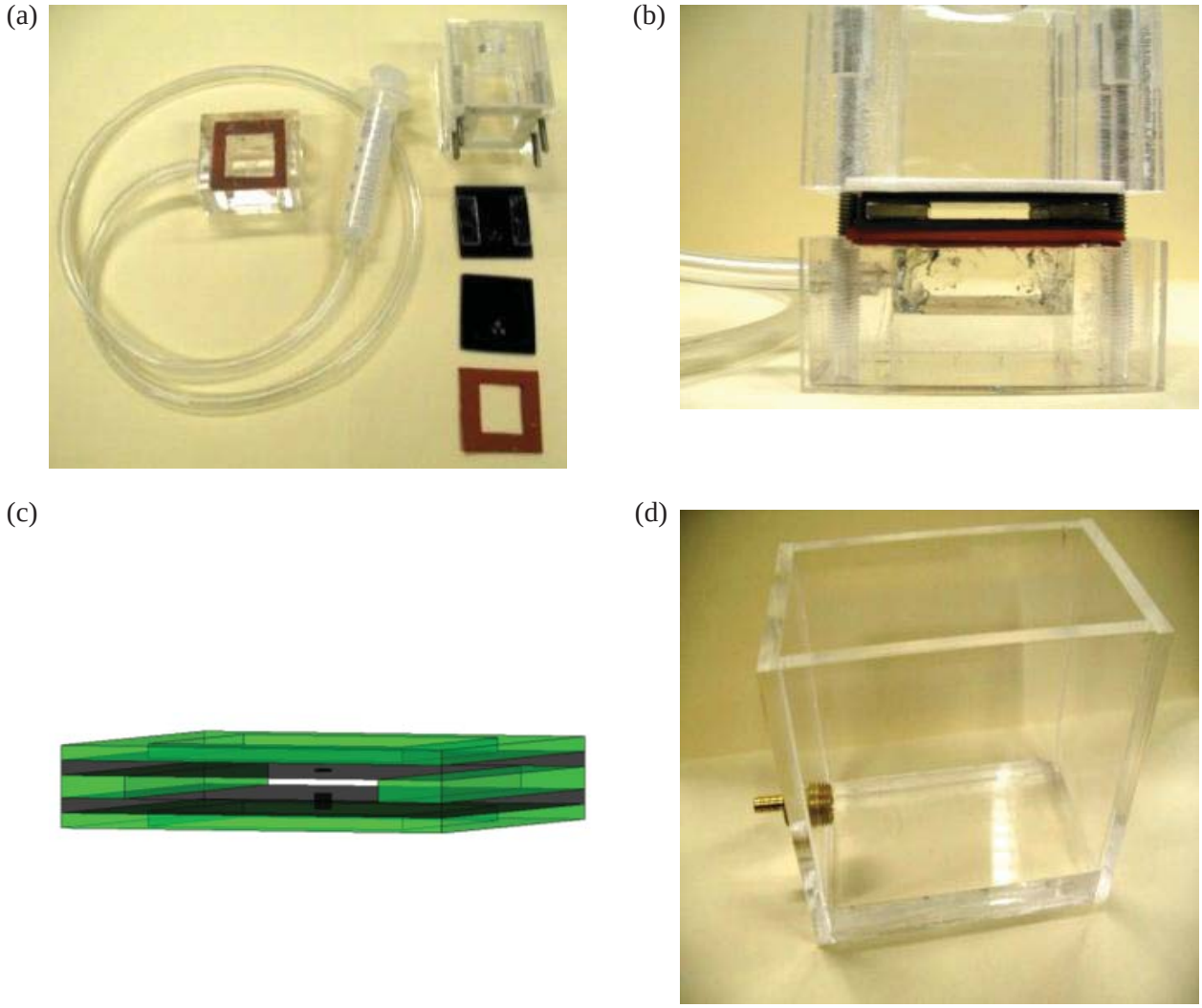

Fig. 5 (a) Overview of the components comprising the experimental apparatus. (b) Close-up of the assembled experiment. (c) Sketch of the silicone gasket/copper plate/acrylic spacer sandwich. (d) Small argon holding tank to shield the experiment from atmospheric oxygen.

4.4. Experimental procedures

Once the system was constructed and cleaned, the copper plates were placed on a heating pad to prevent the gallium from solidifying on contact with a cold surface. The gallium used throughout the project was stored in a container in a freezer to keep it in its manageable solid form and brought to its melting point before experimentation by placing the container on the heating pad with the copper plates. When the gallium became molten the pieces of the experiment were assembled in a 30 gallon closed top argon tank where the gallium was pipetted into the holes in the substrate. The acrylic structure was then assembled with screws around the silicone rubber and copper sandwich then placed in the small acrylic containment chamber. A digital SLR and later a high-speed camera with a microscope zoom lens were used to image the system during activation. The pressure pulse in the system was typically generated by hand, but

a syringe pump was also used in an attempt to quantify the volume of argon needed to switch the system; see Figure 6.

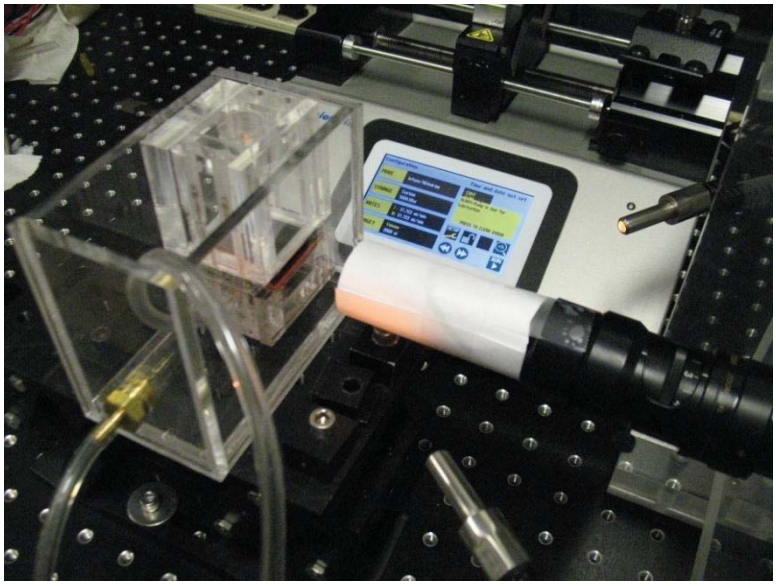

Fig. 6 Liquid-metal bridge switch apparatus inside a small argon containment tank along with a camera lens and syringe pump used during the experiments.

5. Proof-of-concept: Experimental verification of liquid-metal-bridge connection and disconnection

Utilizing the system described above, it was possible to stably pin the contact line of liquid gallium coupled drops on epoxy coated substrates and achieve the switching behavior needed to realize a conduction modulation device via liquid bridges. A syringe pump was used to repeatedly form and break the liquid bridge on the order of one hundred times with 500 μL of volume being pumped at 0.2 mL/sec. Smaller quantities of volume were also used to switch the system, but required a faster pumping rate. The proof-of-concept for liquid-metal bridge switches is presented in Figure 7.

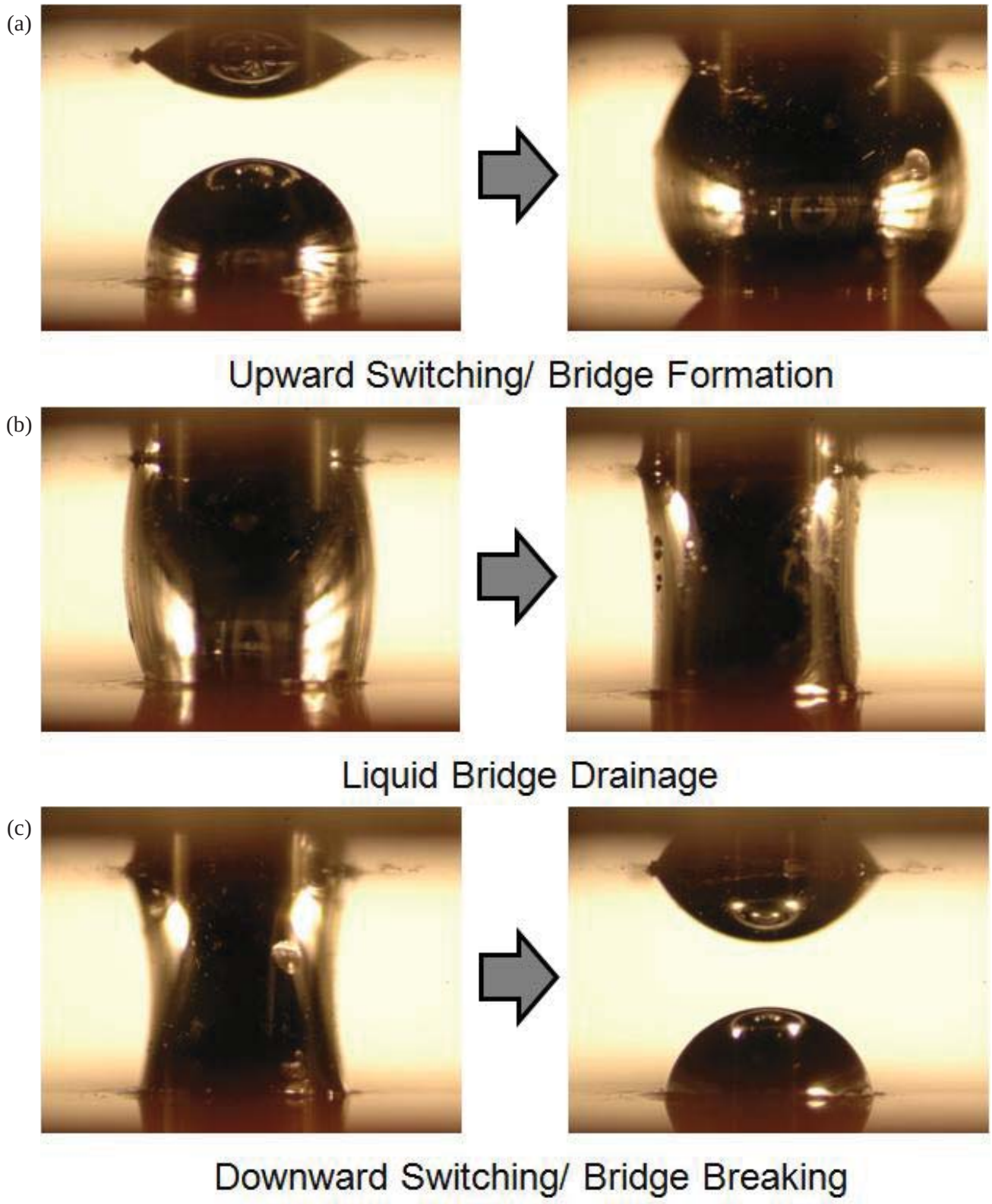

Fig. 7 Series of images showing (a) DDS switching upwards and coalescing with the satellite droplet forming a stable liquid bridge, (b) gallium being drained from the liquid bridge during application of negative pressure gradient and (c) DDS switching downwards and breaking the liquid bridge.

There are three shapes possible for the liquid bridges formed in the system and depend on the relative volume and spacing of the DDS to the satellite droplet; see Figure 8. Closely spaced, large volume systems form convex sided barrels. As the spacing is increased and the volume of the droplet system decreased it is also possible to form cylindrical and catenoidal shaped bridges. Transient cylinder and catenoid shapes are observed during the draining and eventual downward switching process of barrel shapes. The dynamics of the liquid bridge connection and breakage occurred on too short of time scales for a conventional digital SLR camera to capture and necessitated the usage of a high-speed camera that could capture capillary wave phenomenon and determine their phase speed.

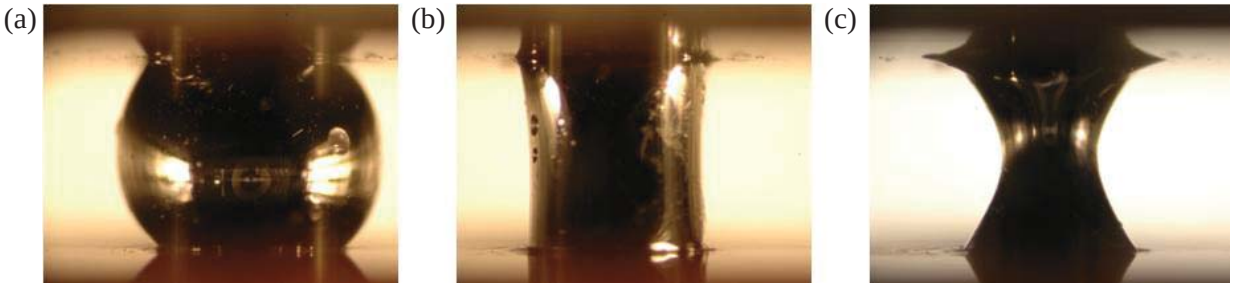

Fig. 8 The three types of liquid bridges observed (a) Barrel, (b) Cylinder and (c) Catenoid.

The process of pressurization, upward switching, and eventual bridge formation occurs within a tenth of a second with most of that time utilized by the pressure building process. When observed, the DDS slowly rises with the increase in pressure, but then quickly accelerates as the system switches from the bottom to top equilibrium energy state. Once the DDS makes contact with the satellite droplet, the rapid coalescence of the high surface tension liquid metals allows a thermal bridge to be formed within a few milliseconds; see Figure 9.

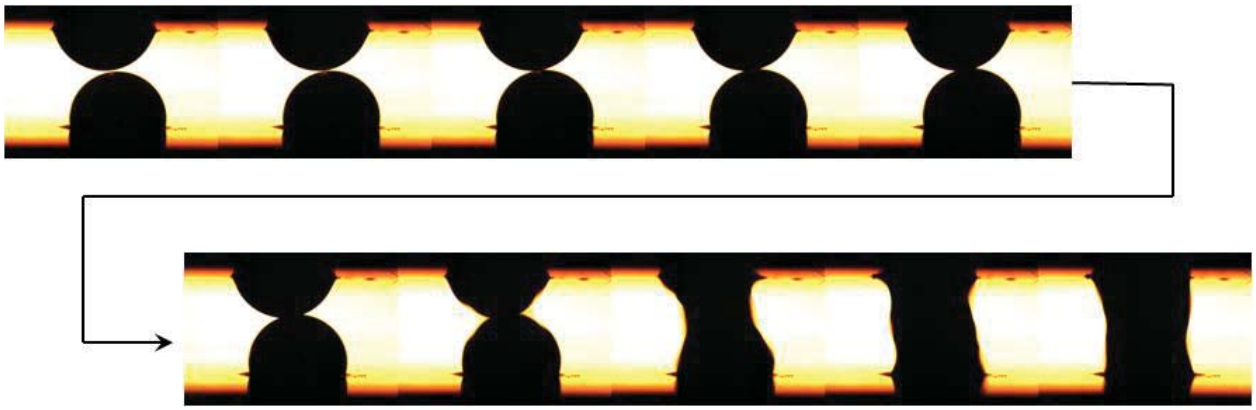

Fig. 9 An 8 millisecond long section of video capturing the rapid liquid bridge formation process. Note, the slight misalignment between the DDS and the satellite droplet can easily be eliminated in more refined experiments in the future.

A similarly fast phenomenon is observed during the liquid bridge breaking process; see Figure 10. Starting from a barrel-shaped bridge, liquid is slowly drained from the bridge as a negative pressure differential is produced on the bottom of the DDS. Once the DDS switches downward, the waist of the remaining bridge (whether a barrel, cylinder, or catenoid) is quickly reduced until the inevitable breaking of the bridge occurs on an extremely short timescale (less than 1 millisecond.)

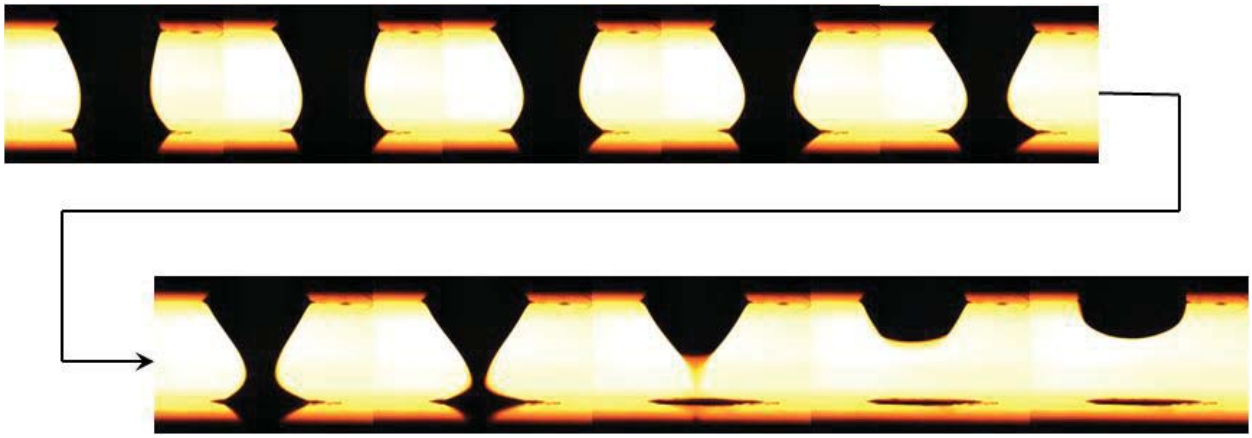

Fig. 10 An 8 millisecond long section of video capturing the dynamics of liquid bridge breaking.

The experimental results show that liquid-metal thermal bridges on coated metal substrates are indeed possible to readily construct and reliably operate. Although no specific heat transfer experiments were undertaken, it is possible to recognize the great heat conduction pathways that liquid-metal bridges open between the two substrates. This is demonstrated in the following section, using both computational and analytical tools.

6. Computational and analytical modeling of the heat transfer

In order to gain insight on the heat transfer capabilities of liquid-metal bridge switches of varying geometries, both computational and analytical models were developed and their predictions were compared. At this stage, the system is simplified in various ways to make the calculations straightforward.

6.1. Computational setup

COMSOL Multiphysics™ software was used to numerically estimate heat transfer performance of the system. The first case, which constituted a baseline throughout the computational studies is a cylindrical bridge between two copper plates with the dimensions of experimental proof-of-concept; specifically a bridge diameter of 1.6 mm (0.063"), plate gap of 2 mm (0.08"), and 38.1 x 38.1 x 1.59 mm (1.5” x 1.5” x 1/16”) copper plates. The bottom protruding droplet is not considered in the analysis, but the material within the bore is considered. Material properties of gallium and copper were applied appropriately; see Figure 11.

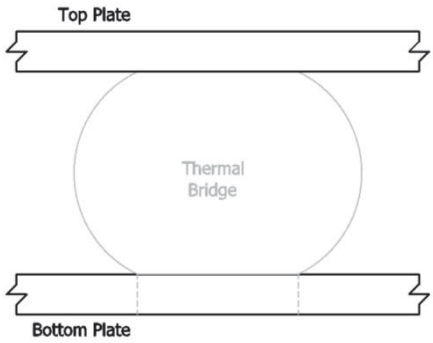

Fig. 11 Simplified geometry used for COMSOL calculation, note the absence of a bottom protruding droplet.

The three-dimensional heat conduction solver in COMSOL was used with initial and boundary conditions that could be recreated in the laboratory at a later project stage. The initial temperature of the upper plate was set to 100°C with insulated boundaries, while the initial temperature of the lower plate was prescribed to 20°C with fixed temperature boundary conditions of the same temperature, 20°C. A mesh was then applied to the system with one refinement to avoid mesh geometry errors; meshes for a single DDS were on the order of 10^4 elements. The spacing between the plates (h), radius of the contact line (R_1), and radius of the bolt circle for arrays (R_{BC}) were varied. To verify the analytical simplification of the different types of thermal bridges, different shapes: barrels, cylinders, and catenaries were also analyzed in COMSOL.

6.2. Analytical formulation

An attempt to simplify the three-dimensional system to one-dimension thermal resistance circuit was also carried out. In these formulations the thermal resistances of the barrel, cylinder, and catenoid shaped liquid bridges (Figure 12) are calculated by integrating a differential form of the resistance equation in the direction between the plates, and the results are presented here:

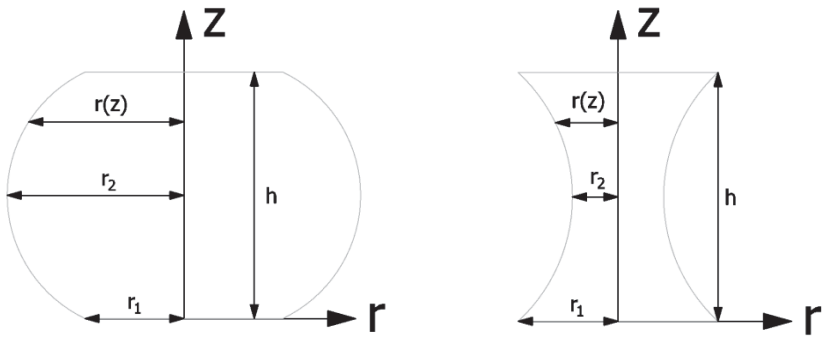

Fig. 12 Coordinate system and dimensions used for analytic calculations.

$$R_{Barrel} = \frac{h \tanh^{-1}\left(\frac{\sqrt{r_2^2 - r_1^2}}{r_2}\right)}{\pi k r_2 \sqrt{r_2^2 - r_1^2}} \qquad R_{Catenoid} = \frac{h \tan^{-1}\left(\frac{\sqrt{r_2^2 - r_1^2}}{r_2}\right)}{\pi k r_2 \sqrt{r_2^2 - r_1^2}} \qquad R_{Cylinder} = \frac{h}{k\pi r_1^2}$$

Heat transfer between plates for a given temperature difference can then be calculated using a modified form of Fourier's law of heat conduction.

$$\frac{\Delta Q}{\Delta t} = \frac{\Delta T}{R}$$

In the copper/gallium system, this analysis is expected to provide a good estimate since the thermal conductivity of copper is very high compared to gallium that any temperature gradients created by the gallium thermal bridge on the copper plates are quickly smoothed and minimized, thus validating the lumped mass model. The same analysis was utilized for arrays; however, depending on the bolt circle radius of the spacing an associated hexagonal area was associated with each liquid bridge.

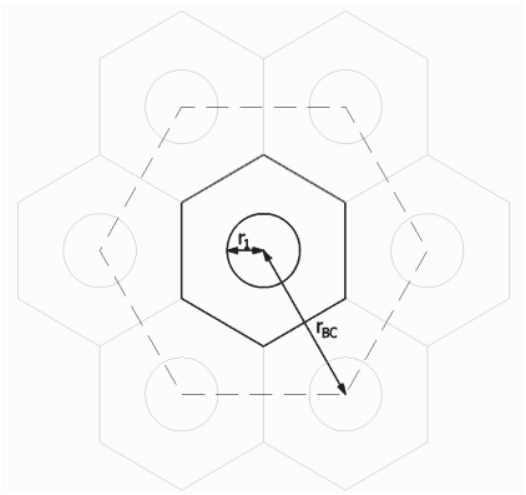

Fig. 13 Schematic of the periodic hexagonal areas associated with staggered arrays.

In a regularly packed array (Figure 13), this hexagonal area would denote the region where conduction through the inert gas and thermal radiation act for each individual thermal bridge providing insight into the turndown ratio of the system in practice. The heat conduction through an array of liquid bridges occupying a specified area can also be calculated with the following equation.

$$A_{Hexagon} = \frac{3\sqrt{3}}{2} r^2 \qquad \frac{\Delta Q_{perArea}}{\Delta t} = \frac{\Delta T}{\frac{\sqrt{3}}{2} R_{Shape} r_{BC}^2}$$

7. Heat transfer and turndown ratio results

When the system is in the Off state, thermal conduction can occur in the argon between the two plates along with thermal radiation. Convection driven heat transfer is not included in the model because of the assumption that the system will be operated in microgravity. The conduction heat transfer in the argon is calculated analytically using the same formulation of 1-D heat transfer of a cylindrical liquid bridge, however, the hexagonal area associated with each thermal bridge is used as the cross sectional area. A constant thermal conductivity value was assumed for argon, where in reality it would have a functional, albeit small, dependence on the temperature of the gas. The thermal radiation calculation also uses the hexagonal area per liquid bridge as the region of exchange between the two plates assumed to be blackbodies of differing temperature. Because of the temperature to the fourth power dependence for thermal radiation, the turndown ratio of a thermal bridge system would actually depend on the temperature of both the heat source and sink. The analysis included in this report assumes a heat sink temperature of 0°C and allows the heat source to vary from 0°C to 500°C. When the system is switched to the On state, the two Off state heat transfer mechanisms continue to act, along with the new conduction pathway through the liquid-metal bridge. The heat transferred per thermal bridge can be readily calculated from the analytic formulation or with COMSOL if a more complex geometry is desired. The turndown ratios displayed on the axes of charts throughout this report will be shown as some number, e.g. 100, which is to be interpreted as a turndown ratio of 100:1. Turndown ratio calculations assume a 3.6 mm bolt circle radius, the closest spacing bridged during experimental efforts except for the case where the bolt circle dimensions are varied.

7.1. Bridge shape effects on heat transfer and turndown ratio

The computational and analytical models were compared for physically observed liquid bridge geometries. The effect of waist radius on the heat flux and thermal resistance does not follow any simple (linear) relationship and is based on inverse tangent and inverse hyperbolic tangent for barrels and catenoids, respectively. Figure 14 shows that the computations agree very well with the analytic expressions for cylindrical and barrel-shaped bridges. Numerical and analytical results for catenoids begin to diverge as the waist area narrows. The baseline case of a cylinder shaped bridge with the 1.6 mm diameter and 2 mm height will be marked with a black circle throughout all of the heat transfer analysis to provide a standard to compare against as different variables change.

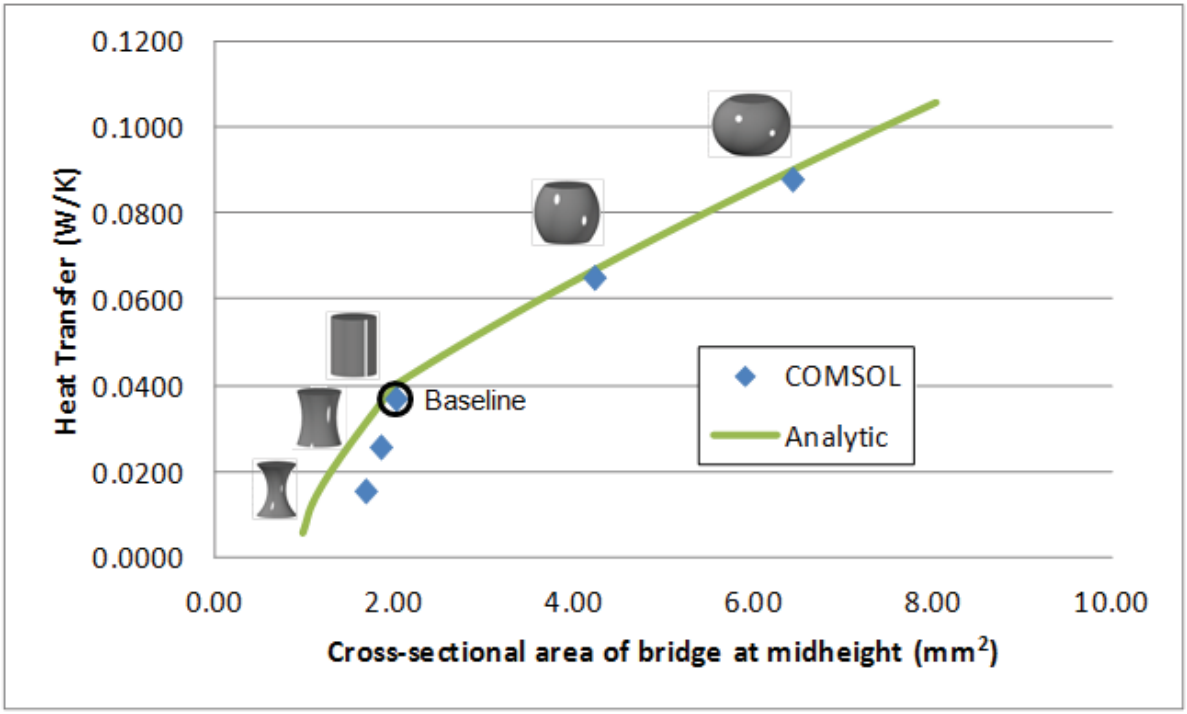

Fig. 14 Comparison of COMSOL and analytic calculations for differently shaped liquid bridges.

Conveniently, the heat transfer metrics of the barrel, which is the easiest shape to create, are many times higher than a catenoid with the same contact line area. Since the contact line for extremely wide barrels remained stably pinned during the experiments, a liquid-metal switch thermal control system would likely involve utilize barrel shaped liquid bridges.

The five data points provided by COMSOL in order from largest to smallest waist area represent the barrel, half barrel, cylinder, half catenoid, and catenoid in Figure 14. Dimensions for the barrel and catenoid were obtained by measuring the diameter of the largest and smallest waists on shapes observed during the experimental portion of the project. Heat transfer per unit cell (a thermal bridge and surrounding hexagonal area) for the different shapes along with the radiation and conduction through argon are shown along with the associated turndown ratios. A turndown ratio of around 200:1 is observed at small temperature differentials in the best case scenario, a barrel. Results from a series of COMSOL simulations are presented in Figure 15 and 16 for heat transfer rate and turndown ratio, respectively.

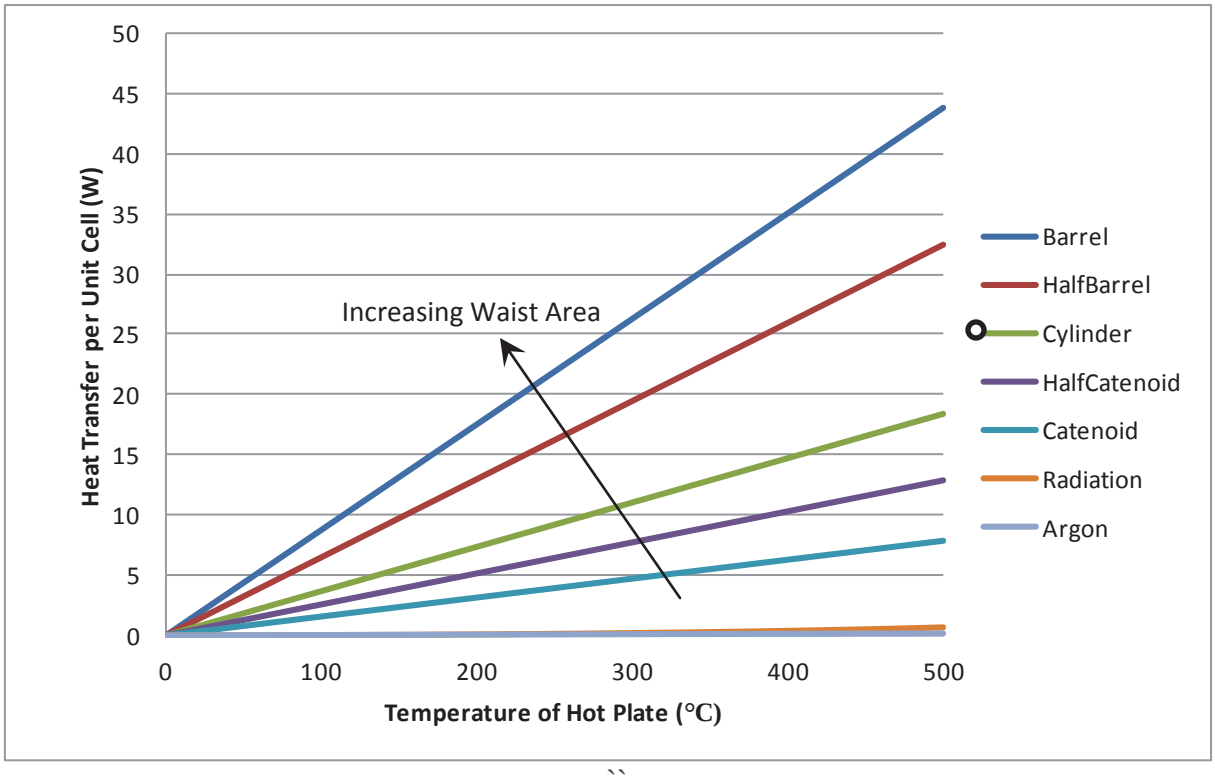

Fig. 15 Heat transfer per liquid bridge of varying shape.

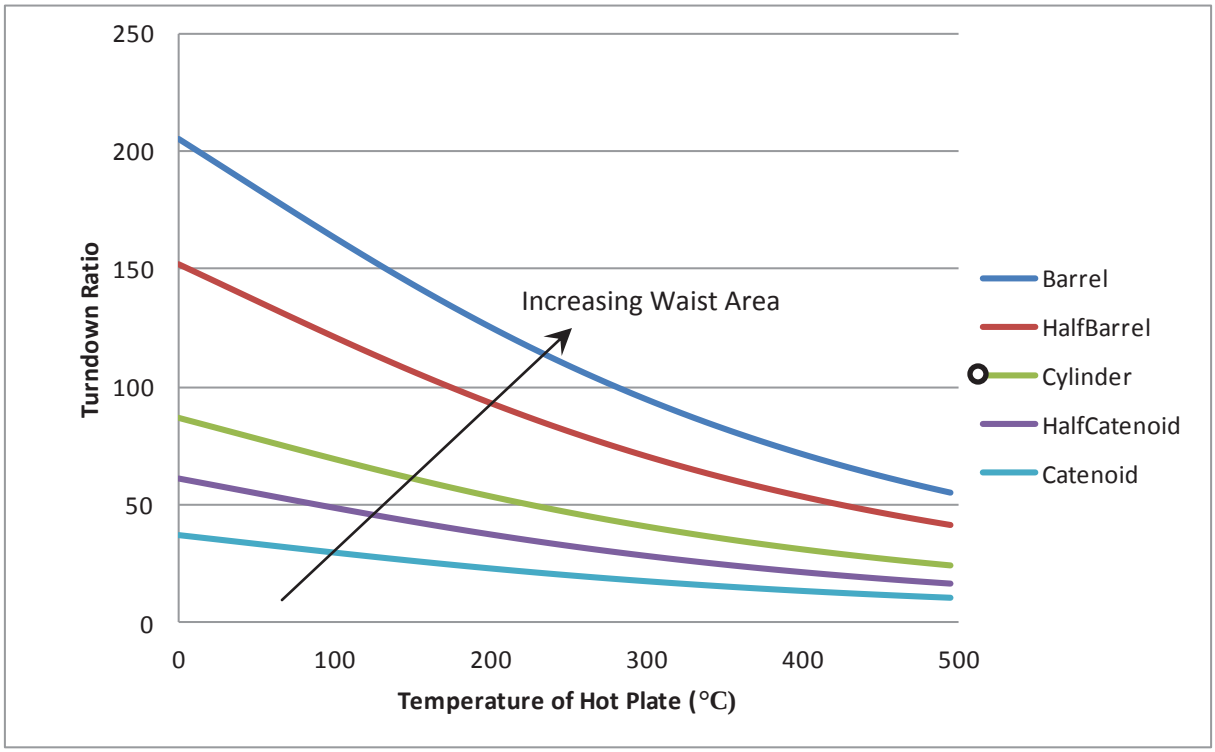

Fig. 16 Effect of liquid bridge shape on turndown ratio for arrays.

7.2. Plate gap effects

The size of the gap between the plates is the next consideration in the heat transfer analysis. In the simplified model used to represent the full 3-D system, increasing the size of the gap results in an almost proportional decreases the two conduction pathways of heat transfer. The amount of radiation heat transfer stays the same regardless of the gap size for the aspect ratio of our system (large plate areas with small gaps.) More closely spaced liquid bridge systems have more optimal thermal properties, but could have the downside of creating system with such "full" barrels that their contact line de-pins from the substrate. The results for the heat transfer rate are presented in Figure 17 and the turndown ratio in Figure 18.

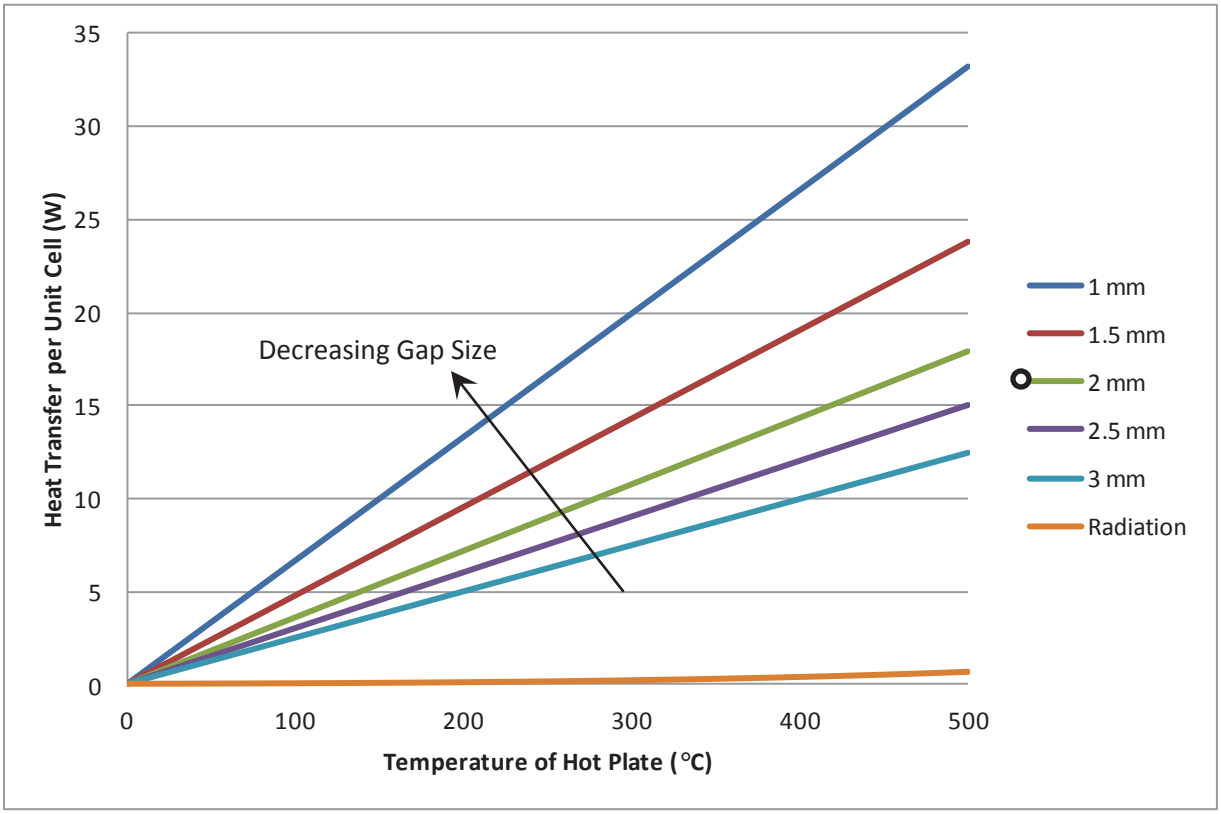

Fig. 17 Heat transfer of a single liquid bridge between plates of different gap size.

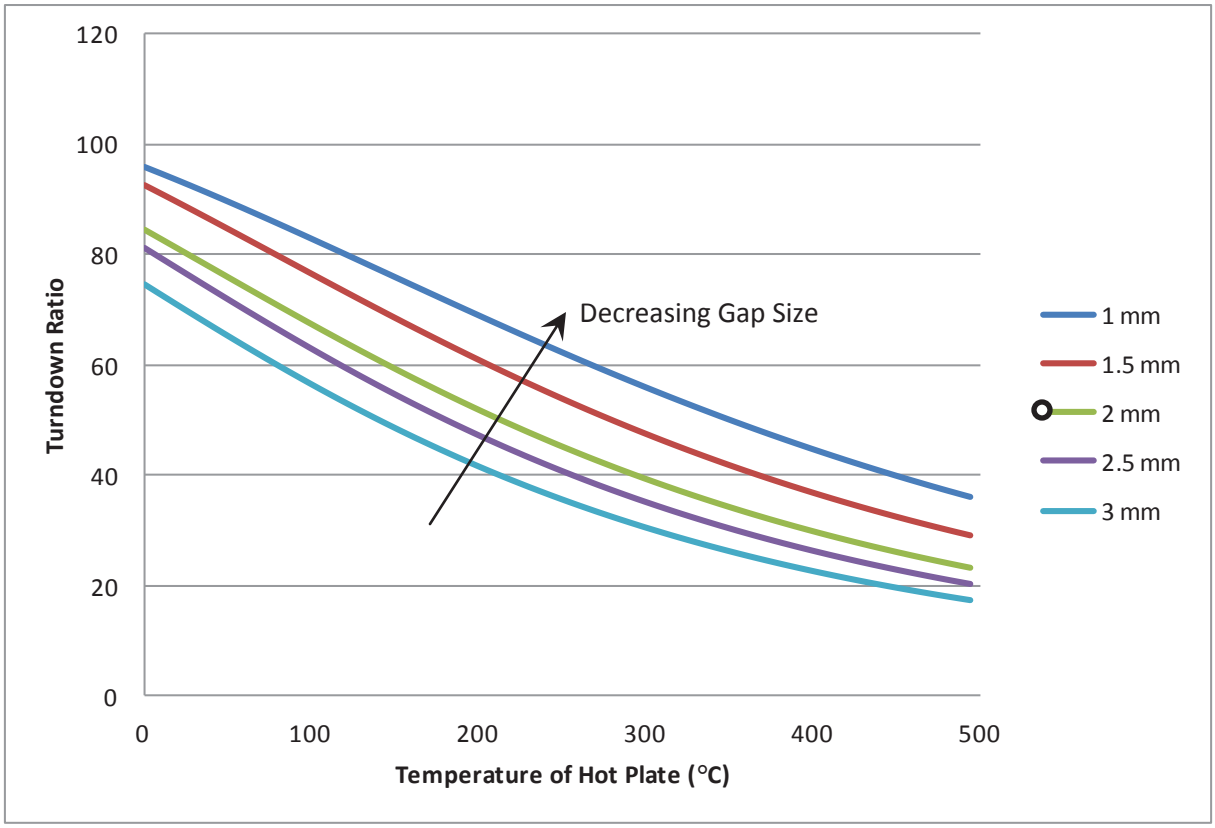

Fig. 18 Effect of plate gap spacing on the turndown ratio of arrays.

7.3. Length-scale effects

The diameter of the satellite droplet contact patch and DDS can also be modified to increase or decrease the cross-sectional area of the liquid bridge. Any change in the area of the highly conducting thermal bridge will drastically modify the heat transfer characteristics of the system. The diameter of the holes in the substrates must be carefully considered, as the stability of systems utilizing surface tension to resist body forces decreases with the length-scale squared. Fortunately, liquid-metals such as gallium have extremely large surface tension allowing for reasonably large scaled systems to be constructed. In Figures 19 and 20, dotted lines represent systems that are possible in theory, but were not proven as a diameter of 1.6 mm was used for the experiments. The 3.6 mm assumed bolt circle radius used in the turndown ratio calculation could also prove problematic for these larger diameter systems since the droplets may collide with their neighbors and coalesce into one large mass if they are spaced this closely.

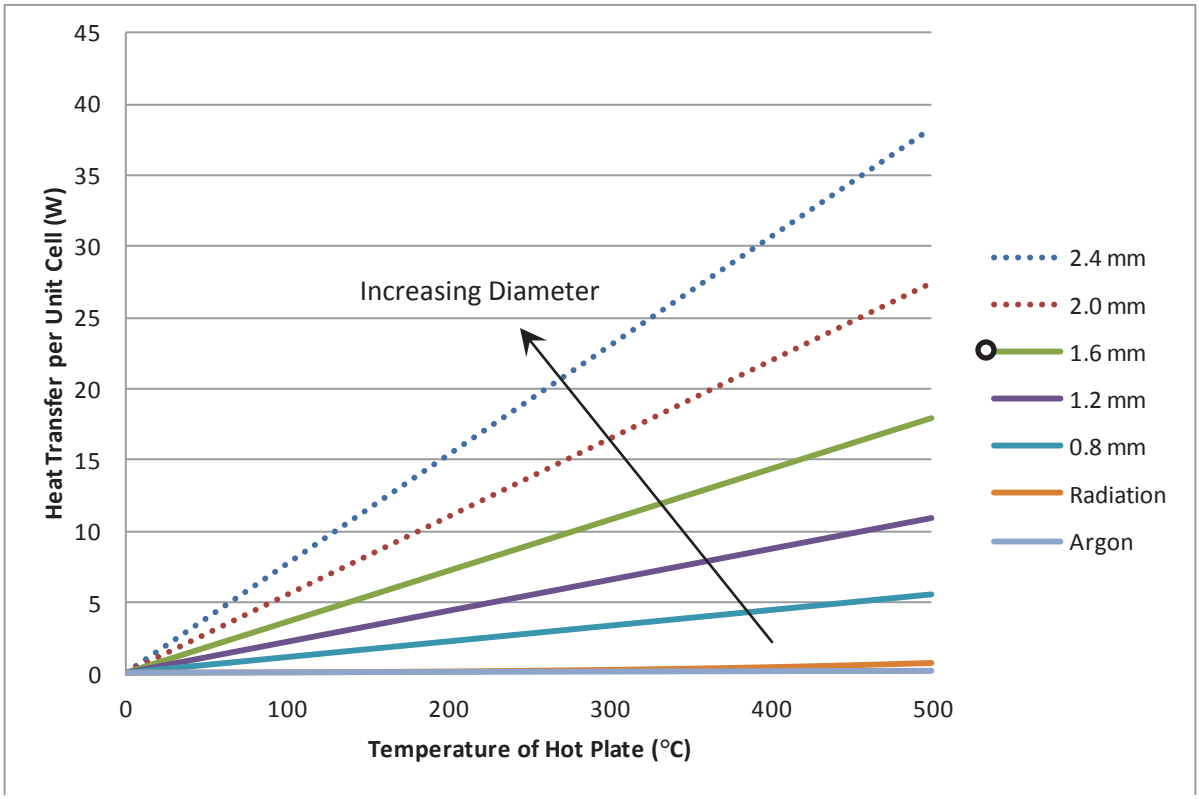

Fig. 19 Heat transfer of single bridges of various diameters.

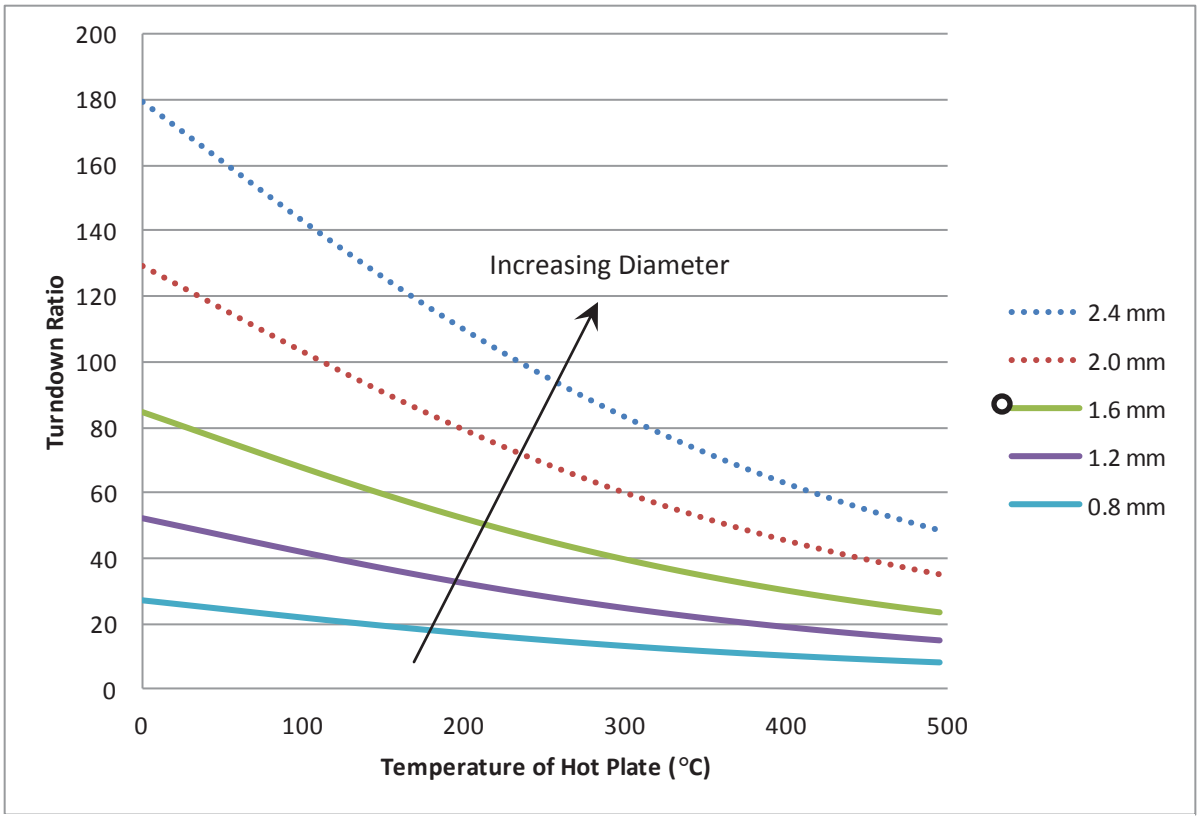

Fig. 20 Effect of bridge diameter on the turndown ratio of arrays.

7.4. Array spacing effects

Since such large turndown ratios are not necessary for the missions under consideration here, the spacing of the array of liquid bridge switches can be significantly increased from the tightest packing (i.e., maximum packing density). The geometry and heat transfer of the liquid bridges remains the same in this analysis. The hexagonal area of the argon filled gap that conduction and radiation occur through increases, reducing turndown ratio. Both COMSOL results (shown in dashed lines) and analytical results (shown as solid line) are included in Figure 21.

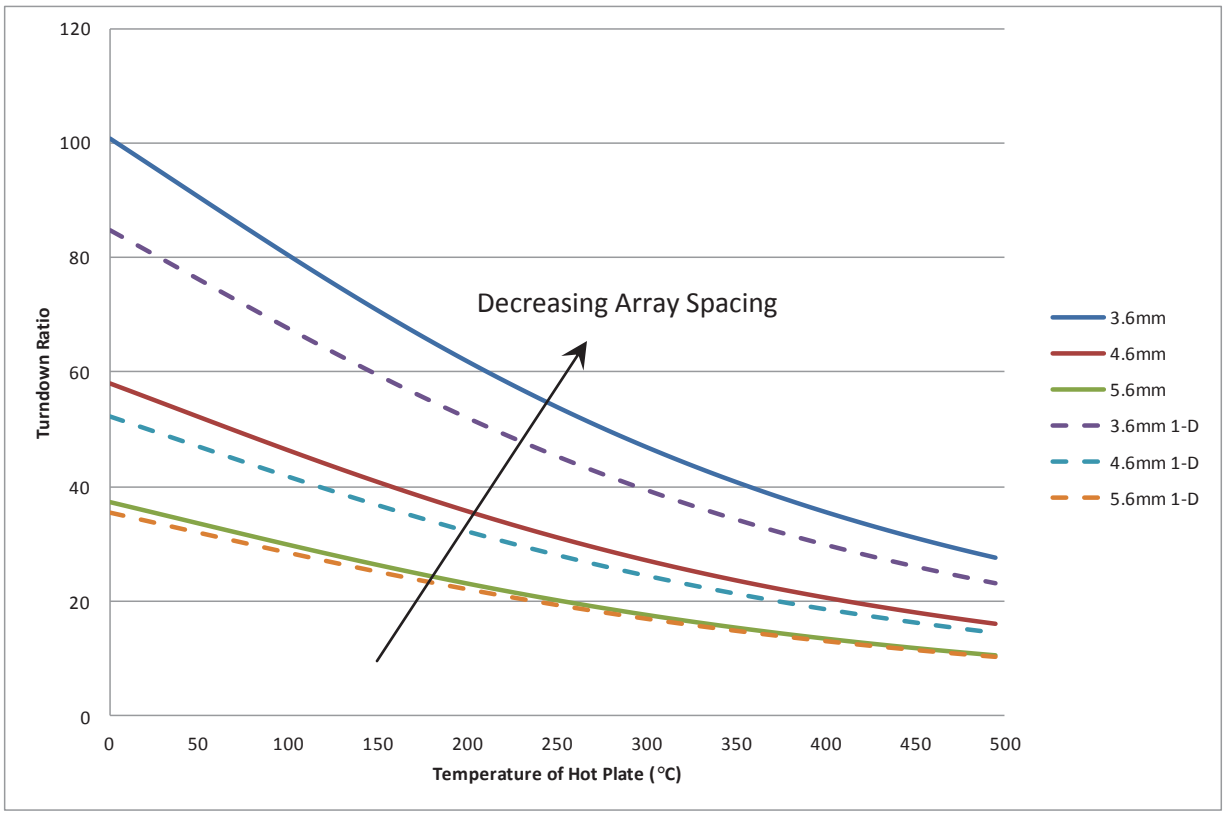

Fig. 21 Effect of bolt circle radius on the turndown ratio of arrays.

These calculations involve a variety of assumptions that would adjust the turndown ratio if taken into account. Including the edges of the array and any structural framework that may be required for structural integrity to maintain the gap between the plates, in the calculation would negatively affect the thermal properties of the system. A variety of steps could be taken to minimize these in a practical system to provide sufficient turndown ratio including a lower thermal conductivity inert gas or no shield gas in the case of systems utilizing another form of actuation besides pressure. Assuming the two plates as black bodies also provides the most conservative approximation for thermal radiation; a practical system would likely utilize reflective material on the heat sink in order to maximize the turndown ratio. Other effects such as thermal Marangoni convection that results from surface tension gradients will inevitably increase the heat transfer through liquid bridges. This increase is likely to be very large due to the strong temperature dependence of liquid metal surface tension on temperature. Even with these approximations,

turndown ratios above 100:1 are readily attainable in a system sharing the geometry of the proof-of-concept experiments.

8. Accomplishment of technology readiness

8.1. TRL-1

Bi-stable switches made by connecting two droplets, each with pinned contact lines, was demonstrated experimentally in 2002 (Steen, P, Matalanis, C., Hirsa, A., and Cox, C., “Capillary Micro-Switches," *Bull. Amer. Phys. Soc.* **47** (10), 129-130, 2002). The development of capillary switches was motivated by applications in microgravity for transporting large packets of liquids via sequentially activated arrays of capillary switches, akin to a “bucket brigade.” Substantial progress was made starting in 2004, when liquid bridge switches were realized using water and Teflon substrates. A bi-stable capillary switch visualized using laser-induced fluorescence is shown in Figure 22, where the switch is initially stable and in the down-state. By application of a small, momentary pressure pulse from below, the switch is made to toggle up, where it becomes stable again in an up-state. Figure 23 shows a bi-stable capillary switch, above which is another plate (Teflon). Upon activation with a pressure pulse, the coupled droplets move up and contact the plate on top and form a stable liquid bridge (second image from the left). Upon application of a negative pressure pulse from below, the liquid bridge is broken, leaving behind a satellite droplet. Note, the exposure time for this photograph (third from the left) was long enough to simultaneously show the before, during, and after images of the liquid bridge being broken. The progress is chronicled in the publications listed below. The final image (fourth from the left) shows the new stable configuration. Upon application of a positive pressure pulse from below, the coupled droplets can move up and contact the satellite droplet and reform the liquid bridge, returning to the state shown in the second image from the left.

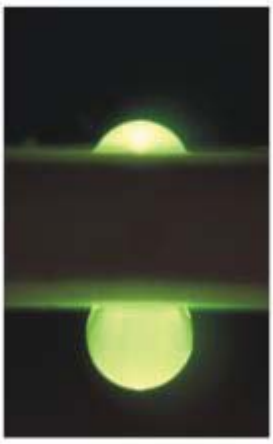

Fig. 22 Water DDS switch in Teflon™ showing bi-stable equilibrium (from Hirsa et al., *Applied Physics Letters* 2005)

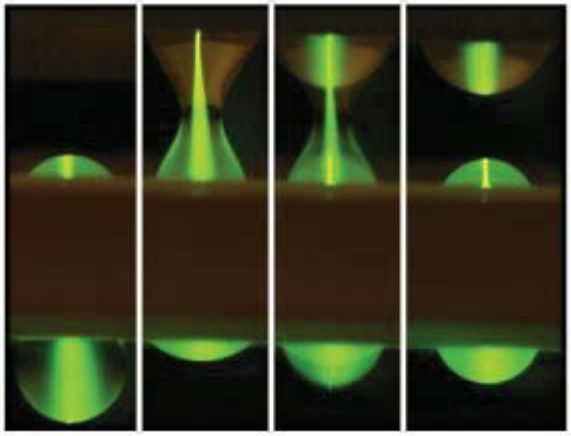

Fig. 23 Water liquid bridge demonstrated on Teflon™ substrates (from 2004 APS-DFD conference presentation).

8.2. TRL-2

In 2009 the PI and Dr. Bernard Malouin (at that time a graduate student in the PI's lab), demonstrated bi-stable capillary switches using a liquid metal at slightly elevated temperature (~40 °C). Figure 24 shows a bi-stable switch made of gallium on a Teflon substrate. The switch is initially in the down state. Upon a momentary, positive pressure pulse applied from below, the switch is made to toggle up. The switch will remain in the new stable state, with most of the gallium in the upper droplet, until it is toggled down with a negative pressure pulse.

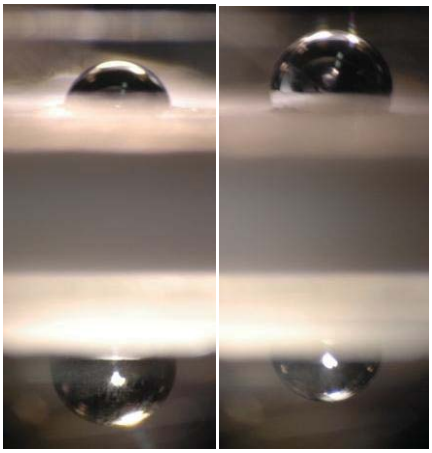

Fig. 24 Gallium capillary switch demonstrated in Teflon™.

8.3. TRL-3

Now completed, the proposed goals of our Variable Heat Rejection-Phase I schedule fulfilled this technology readiness level. The experimental proof of concept, shown in Figure 25, using liquid gallium in a coated metal substrate demonstrated during this phase show that conduction heat transfer through a device can be modulated using liquid bridge switches.

Fig. 25 Gallium capillary bridge demonstrated on copper substrates and removed from experimental apparatus.

Both computational models illustrated in Figure 26 and analytical tools were also utilized to estimate the heat transfer capabilities of the device including heat transferred per liquid bridge and turndown ratio of an array. These results can be used to determine the optimal geometry of a practical device that modulates heat transfer.

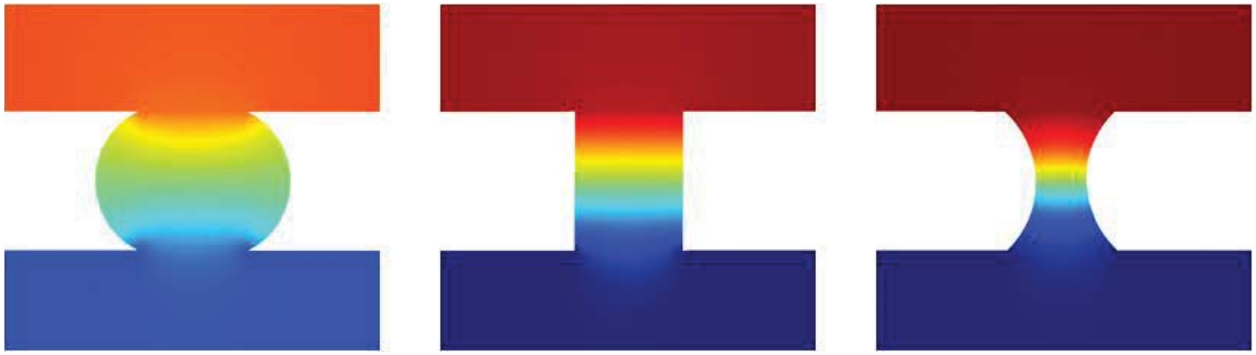

Fig. 26 Illustrative COMSOL contour plots of different bridge shapes taken at the same time step in the analysis, showing barrel shapes transfer heat more effectively.

9. Future steps

9.1. TRL-4

The analytical and numerical calculations undertaken during Phase I of the project would be refined to account for higher order heat transfer effect and integration into a specific type of mission profile. Calculations would be needed to determine the effect on heat transfer and structural rigidity of both boundaries and structural elements. These models would likely be specific to the size and shape of the system necessary for a specific amount of heat transfer capability. Experimental measurements of heat transfer for a system similar to the proof-of-concept using thermocouple temperature probes and non-invasive thermal imaging would validate the models created during TRL-3 of the technology's development.

This stage of development would also allow enough time to obtain and test other construction materials such as magnesium for the substrate. The lack of availability and elaborate requirements for machining magnesium could both be tackled, allowing a huge reduction in system mass if proven compatible with a polymeric coating and gallium. Other types of actuation (both active and passive) including electrostatic or mechanical would be investigated to increase viability and stability of the system in a space environment.

9.2. TRL 5/6

These two technology readiness levels involve integration of liquid-metal bridge switches into a mission-capable system that optimizes the key performance metrics such as turndown ratio and system mass by utilizing the wealth of information discovered in earlier phases of the project. The prototype system would be constructed and benchmarked in a vacuum environment, allowing all of the previous experimental, analytical, and numerical work to be validated. In the project's current nascent state, it is possible that a future finding or requirement will modify the system that we currently project for these later phases into a slightly or significantly different device utilizing the same liquid bridge switch principle.

10. Critical risk analysis

10.1 Materials

The unique combination of materials required to create liquid-metal bridges will need focus throughout the development of a device utilizing them. Gallium's near room temperature melting point provides a perfect match for the liquid bridge system, but also makes alloying with other metals favorable at lower temperatures than the process typically occurs for more common metals such as aluminum and copper. System components will need to be made of compatible metals that are not rapidly corroded by this alloying action. The interesting wetting properties of gallium along with its high surface tension also make investigation into polymeric coatings a necessity. Metals comprising the substrates for the DDS and satellite droplet holder plate will need a permanent and robust polymer coating such as Teflon™ in order to stably pin the contact lines of gallium throughout the system.

An increase in the operating temperature envelope of a liquid-metal system is another necessary thrust of material research. An overview of the temperature range of the current system is shown in Figure 27. The upper envelope of the system is most likely going to be defined by whatever non-wetting coating placed on the metallic substrates, since polymers begin to degrade far before the solids components melt or liquid components vaporize. The effect of volume differences through temperature and phase changes for all materials involved will need to be understood for a practical system to be realized. Although gallium's melting point is defined at 29.8°C, the liquid phase has been observed to supercool below 0°C in the experimental phase of this project and the literature. If a more robust low-temperature solution is required, other liquid metals such as gallium alloys can be used at fairly significant cost to thermal properties.

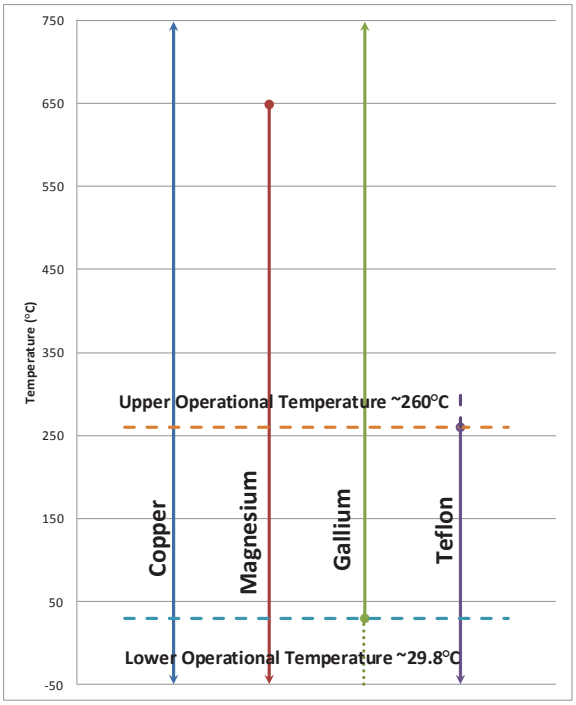

Fig. 27 The temperature operational envelope of a liquid bridge thermal control system.

Gallium and other liquid-metals have a tendency to form an oxide layer in oxygen rich environments such as the Earth's atmosphere; see Figure 28. A liquid bridge system must be assembled and enveloped in an inert shield gas such as argon or held in a vacuum throughout its lifecycle to prevent the formation of gallium oxide which negatively affects system performance.

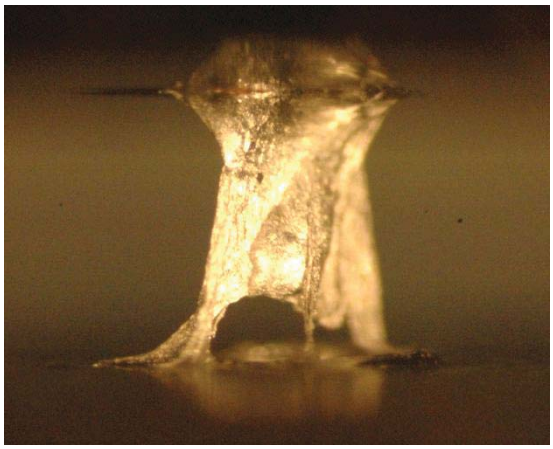

Fig. 28 Gallium oxide skin on a liquid bridge system exposed to the atmosphere.

10.2 Stability and control

The liquid bridge system must be able to withstand accelerations and vibrations in order to be used on a space-travelling vehicle. Fortunately, DDS systems can be designed to resist the most extreme accelerations, making removal of the coupled droplets from the substrate very difficult. If larger diameter bridges are desired and launch is expected to be the maximum acceleration the system undergoes during its service lifetime, the gallium droplets can be cooled to their freezing point almost permanently bonding them to their substrates.

Activation of large arrays of liquid bridges can be achieved through a variety of means depending on the redundancy and thermal control desired. Each bridge can be actuated individually, which would provide an extremely robust system against failed components but the additional mass may not be justifiable. Arrays could also be switched in series, where a small pressure pulse leads to a cascade of thermal bridge switching along a set as shown in Figure 29. The least robust activation is switching an entire array in parallel with a fairly significant pressure pulse, though simple, a single ejected droplet from a DDS could lead to a failure of an entire region of the thermal control system.

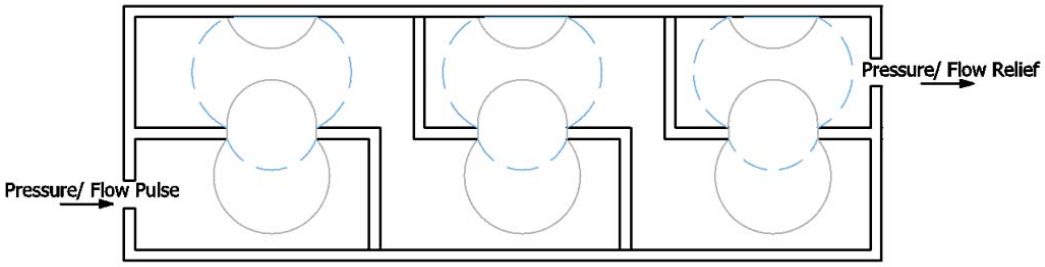

Fig. 29 Schematic illustrating the principle of series actuation.

If active thermal control can be sacrificed for a specific mission; passive activation using the expansion of a gas (Figure 30), deflection of a shape memory alloy, or change in shape of a bimetallic sheet would almost certainly provide the most robust actuation possible. The minimal amount of parts to fail along with the ability to set the temperature at which the system activates without electronic or mechanical intervention would provide an elegant solution to a rather complex problem.

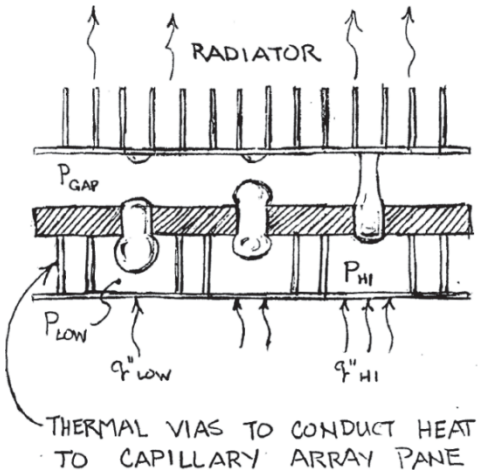

Fig. 30 Diagram of a passively activated system utilizing thermal expansion of gas.

11. TCS mass

The mass of a system entirely depends on the desired amount and area over which heat rejection must occur. A passively activated sample system's mass, with the maximum liquid bridge packing arrangement capable of removing ~100 W/°C over an area of 0.1 m^2, can be estimated; see Figures 31 and 32. The substrate which contains the array of DDS's comprises most of the system mass with the liquid bridges (both DDS and satellite droplet), pressure vessel, and structural elements also contributing.

Substrate		
Copper	843	g
Magnesium	248	g
Liquid Bridges		
Gallium	95	g
Pressure Vessel	34	g
Pillars	40	g
Copper Option	1012	g
Magnesium Option	417	g

Fig. 31 Total mass for copper and magnesium based thermal control systems.

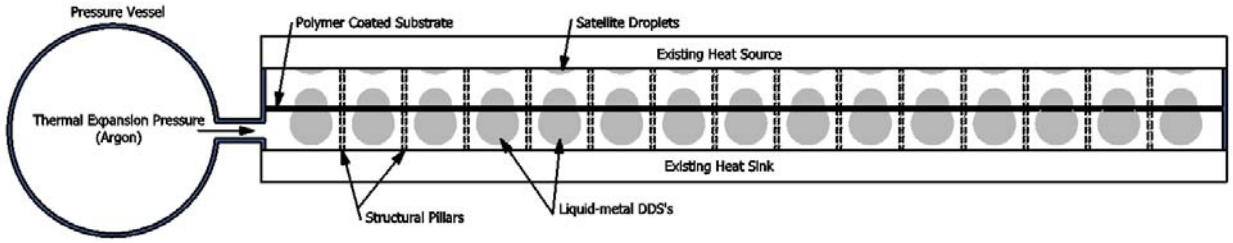

Fig. 32 Illustrative passively activated system for total mass calculations.

This estimated system mass assumes some of the system would be integrated into existing structural and thermal components of a spacecraft. A space vehicle designer may be able to optimize the system mass for a variety of applications requiring localized variable heat rejection over millimeter scales all the way up to meter scale systems by similarly utilizing other spacecraft components. Using lighter materials such as magnesium and trimming excess weight enables a very significant decrease in system mass.

12. Concluding Remarks

Here we showed the feasibility of liquid-metal bridge switches for modulating local heat transfer. Through design and experimentation we demonstrate that technical hurdles including liquid metal surface oxidation and contact line depinning can be readily eliminated, making practical systems possible. The extremely high surface tension of gallium, along with its excellent thermal and flow characteristics, have made possible a novel method to control heat transfer. Copper, with its excellent thermal conductivity, was shown to be a suitable candidate due to its chemical compatibility with gallium. By use of a suitable coating, it was shown that copper can be utilized to make very effective thermal switches with gallium. Optimal system geometries were identified.